SPA CE CRAFT AUTONOMY IN THE NEW MI L LENNIUM

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NASA's New Millennium Program (NMP) is designed to dramatically reduce mission costs and enable new and more frequent exploration missions. The program is structured into live technology teams consisting of industry, government and academia representatives. This paper discusses the role of the Autonomy technology team in the NMP and the development process defined by the team to mature these technologies for flight readiness.

The New Millennium Autonomy Team is leading the development and demonstration of revolutionary autonomy technologies which are needed to fulfill the Program's vision of 21 st century spacecraft and ground operations capabilities and functions. The Autonomy Team has identified and is developing the following technologies: Remote Agent, Autonomous Guidance, Navigation and Control, Autonomous Science and Mission Operations, and multi-platform coordinated missions. To facilitate this effort, the team has developed a roadmap outlining the technologies required for the first five missions. This paper describes what the roadmap process is, what the technologies are that have been identified for flight on the first mission, the criteria for their selection, and the technology challenges, These technologies have the potential to revolutionize operations of deep space and near Earth missions, and to enable NASA's vision of a "virtual presence" in space.

AN OVERVIEW OF THE NEW MILLENNIUM PROGRAM

In NASA's vision of space exploration and Earth observation for the 21st century, human presence is extended beyond Earth by establishing a "virtual presence" in space in order to expand scientific understanding of the universe.. This vision can be realized by using a fleet of individual spacecraft to explore many diverse targets among the planets, their moons, and small bodies in the solar system; and by using coordinated networks of spacecraft to investigate dynamic, complex systems - such as Earth's atmosphere - and detect (and perhaps image) extrasolar planetary systems. Our "presence" in space will be in the form of' numerous small spacecraft; our accumulation of knowledge accomplished through the continuous ret urn of science data to Earth. From Earth, we will be electronically y linked to the far reaches of space.

Fulfilling this vision for the 2 1st century space exploration and Earth observation depends on new capabilities to reduce development, launch, and operations costs; increase mission frequency; and enhance scientific observing and data gathering capabilities. The goal of NASA's New Millennium Program (NMP) is to enable 21 st-century missions through the identification, development and flight validation of key technologies. These critical technologies will be validated so that future science missions can take advantage of them without assuming risks inherent in their first use. NMP technology-validation flights, to be launched during fiscal years 1998-2000, will also provide opportunities to capture meaningful science.

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The New Millennium Program has established several integrated product teams (1 PDTs) that are working in a coordinated and cooperative effort to identify, develop and deliver focused technologies that are central to enabling NASA's vision. The areas selected for 1 PDT focus are those in which a range of emerging breakthrough technologies offers the promise of affordable solutions to key capability needs for the 21st century, There are six IPDTs: Autonomy, Microelectronics S ystems, Instrument S ystems, in situ Instruments and Microelectromechanical Systems (MEMS), Modular Architecture and Multifunctional Systems, and Communications Systems. The Autonomy IPDT and its work is the primary focus of this paper and will be discussed at length in later sections.

The Microelectronics Systems IPDT is developing and demonstrating technologies for a miniaturized, highly integrated, three dimensional avionics architecture that subsumes --into a single "subsystemless" architecture -- the functions of the following traditional subsystems: attitude control; command and data processing; power management; mass data storage; and all payload interfaces. The key drivers for development in this area are the reducti on of mass, volume and power consumption for the spacecraft electronics.

The instruments and in situ instruments and Ml EMS IPDTs are focusing on reducing the mass and power requirements of instruments and mechanical components. Specifically y, these IPDTs are addressing the construction of qualifiable, flight ready systems; the development of highly integrated systems such as chemical laboratories, optical benches, inertial navigation and micropropulsion units, or vacuum microelectronics; improvements in the design, packaging, interfacing, networking and qualification of systems specifically for space applications; and demonstration of revolutionary concepts that might be less mature than items in the previous categories.

The Modular Architecture and Multifunctional System IPDT is focusing on revolutionary advances in mechanical, thermal, structural, power, controls, and chemical system engineering. Particular emphasis is being placed on technologies having the potential to provide order-of-magnitude increases in spaceflight system capabilities.

The Communications System IPDT is responsible for identifying and developing telecommunications technologies that can significantly reduce spacecraft mass, recurring engineering costs, and total life-cycle costs through greater spacecraft independence and autonomy from ground control.

THE NMP AUTONOMY TECHNOLOGY TEAM

What is Autonomy?

Automation and autonomy both refer to systems which assume tasks that were previous] y assigned to humans. However, automation implies that the system performs the task very mechanically, essentially by rote. The system has been given detailed instructions as to how to do the task. Autonomy implies goal-orientedness; we expect a certain outcome without expecting that we know too much about how this outcome will be accomplished. [1] It maybe harder to predict the actions of an autonomous system, but such systems will be more dependable because they tenaciously pursue their goals despite changing circumstances. 'J'his makes prediction of their detailed behavior unnecessary. In fact, part of the goal of autonomy is that the system may perform better than our expectations because it is closer to the data. This powerful and special attribute of autonomy offers

much operations simplification opportunities. Autonomy and automation can be summarized and contrasted in Table 1.

Table 1
AUTONOMY VS ALJTOMATION

Automation	Autonomy
- Mechanistic and relatively inflexible	- Goal oriented and adaptive
- Assumes a well-defined environment	- Enables operation in uncertain environments
- Requires design of complex, detailed procedures	- Design is more easily defined, *rule-based* behavior

Table 2 shows more detailed descriptions of the key functional areas and technologies required to accomplish complete spacecraft autonomy.

Table 2
SPACECRAFT AUTONOMY AREAS OF INTEREST

III1ITWC'I'ION AL AREAS	DESCRIPTION
AUTONOMY SYSTEM ARCH ITECTURE	• Onboard & Ground • Framework that structures system and insulates details
HIGH-LEVEL COMMAND EXECUTION	• Goal directed acti vi t y • Adapt to unforeseen mission circumstances • F.vent driven sequencing • Concurrent operation 01 tasks
ACTIVITY PLANNING, SEQUENCE GENERATION, VAT.TDATION, & RESOURCE MANAGEMENT	• Continuous planning, contingency planning • Adapt configuration to commands & environment • Onboard sequencing validation • Conflict detection & resolution
ANOMALY RESOLUTION	• Fault detection & resolution
ROUTINE SELF-MONITORING & MAINTENANCE	• Self monitoring & selective health reporting • Downlink engineering data management • Self calibrating & self checking
MISSION PLANNING, NAVIGATION & CONTROL (A ttitude, stabilization & pointing)	• Onboard orbit determination & trajectory planning • GPS attitude & position determination • Onboard maneuver design, path planning, constraint checking & sequencing • Precision pointing • Feature tracking, target relative maneuvering, station keeping • Collision avoidance
CONSTELLATION M ANAGEMENT	• Intercommunication & cross links, formation management • Station keeping • Operat ion of spacecraft networks • Data fusion, sensor fusion

PAYLOAD (SCIENCE) PLANNING	•Science goals to sequences, capture serendipitous science •Distributed payload utilization planning
PAYLOAD INFORMATION PROCESSING	•Optimize science downlink information •Adaptive object recognition •Information sampling, editing and compression
MISSION OPERATIONS INFRASTRUCTURE	•EEIS architecture •Multimission process control •Intelligent user interface
TRACKING & DATA TRANSPORT	•Automated ground-spacecraft link and ground station scheduling •Decrease downlink analysis
AUTONOMY HARDWARE	•Optical navigation camera, feature tracker •Miniature GPS •Ranger

The NMP Autonomy Team Constituents and Charter

The Autonomy IPDT is leading the development and demonstration of revolutionary autonomy technologies that are needed to fulfill NASA's vision of the 21st century spacecraft and ground operations capabilities and functions. The Autonomy IPDT has identified those capabilities that significantly reduce the cost of mission operations and enhance spacecraft functionality. Care was taken to avoid focusing on incremental improvements to missions operating in today's environment with existing architecture and operations constraints.

The Autonomy IPDT has two co-leads, representing the Jet Propulsion Laboratory (JPL) and NASA Ames. The Autonomy 1 PDT consists of nine members from government, industry, non-profit organizations, and academia. All IPDT members have voting privileges with decisions arrived at by majority vote. The Autonomy IPDT also has two cooperating partners. Cooperating partners are ex officio members of the IPDT who may provide input but can not vote. These members represent suppliers, focused technology efforts and technical consultants in very specialized areas.

The Autonomy IPDT provides a systems approach in the balanced design of operable missions, spacecraft core and payload systems, and ground operations functions to ensure that operations cost objectives are met and that standard tools and architecture emerge which underpin future NASA missions, Care is exercised to avoid focusing too heavily upon one element of the mission, or the spacecraft and ground systems without due regard for the higher-level system and mission performance. Concurrent with improvements in the spacecraft's autonomy, ground system autonomy will be developed and demonstrated to reduce the operational workforce and its attendant costs. The base mission design is for zero operators between the principal investigator and the flight system, known as the Justified Operations concept.

The product of the Autonomy 1 PDT will be the flight and ground software and hardware needed to enable the on-board and ground-based autonomous capabilities and the associated computer-based tools and architecture required to replicate these capabilities in subsequent missions. The government's role will include concept and algorithm development, flight software implementation and hardware breadboarding; the industry role

will be similar and include hardware development; and academia will provide the basic research into autonomy, artificial intelligence, and related computer science topics. The Autonomy IPDT has developed technology roadmaps showing the long term vision in the NMP context, as well as details on the specific approach, performance, schedule and cost of developing and validating individual technologies that support that vision.

TECHNOLOGY ROADMAP DEVELOPMENT

The technology roadmap is the phased technology development plan for New Millennium. It is a living, document that will be updated at least twice a year. NMP will solicit for new IPDT membership annually and the solicitation process will bring new technologies to refresh the tech nolog y roadmap. The roadmap will not capture all technologies available in the national pipeline. It only captures the most critical ones for NMP. The selection is based on impact on the 21st century science missions, revolutionary nature of the breakthrough and risk reduction by validation flights. The scope of the roadmap is guided by science and exploration needs and they are developed through the New Millennium Working Group.[2]

Roadmap Philosophy

in order to achieve the stressing goals being pursued by the New Millennium program, a coordinated plan and execution of technology development and integration must be conducted. A chief contributor in achieving this level of integration and coordination by a diverse, geographically disparate team is the development and continued use of a program Roadmap.

A program roadmap is not a program plan, nor is it a program schedule of activities, A program roadmap is a graphical representation of the major program elements, their relationships, and intermediate and long term goals for the program. These elements are laid out along a general timeline with major points of confluence as described and used in the following paragraphs.

Roadmapping Process

The primary goal of establishing and maintaining a program roadmap is to provide a vision of the program that all members of the program team, from m anagement to developer, can share and work together toward. The NMP team believes that a common vision for the program is critical to overall program coordination and success in achieving overall program goals.

The process of program roadmapping has been an instrumental part of a methodolog y called User Centered Engineering (UCE) and has been refined through various programs over the past 10 years by the Advanced Research Projects Agency (ARPA). This methodology makes the "user" a key member of the development team with daily i nteractions with most every level of program Staff. This approach gives the user a much larger responsibility in helping, to assure a successful and useful product.

Another major feature of the UCE methodology is that it ensures a structured and prototyping approach. This process involves coordinated technology development; Technology Integration Experiment.s (1'ii+), focused at providing new operational capabilities; Integrated Feasibility Demonstrations (11'11s) which lash together related TIE results to illustrate a prototype operational capability; Multiple IFDs may then be

coordinated as stepping stones toward an overall operational capability - often in the form of an Advanced Technology Demonstration (ATD). This process has been adopted and refined by the NMP to fit their operational needs and is illustrated in Figure 1.
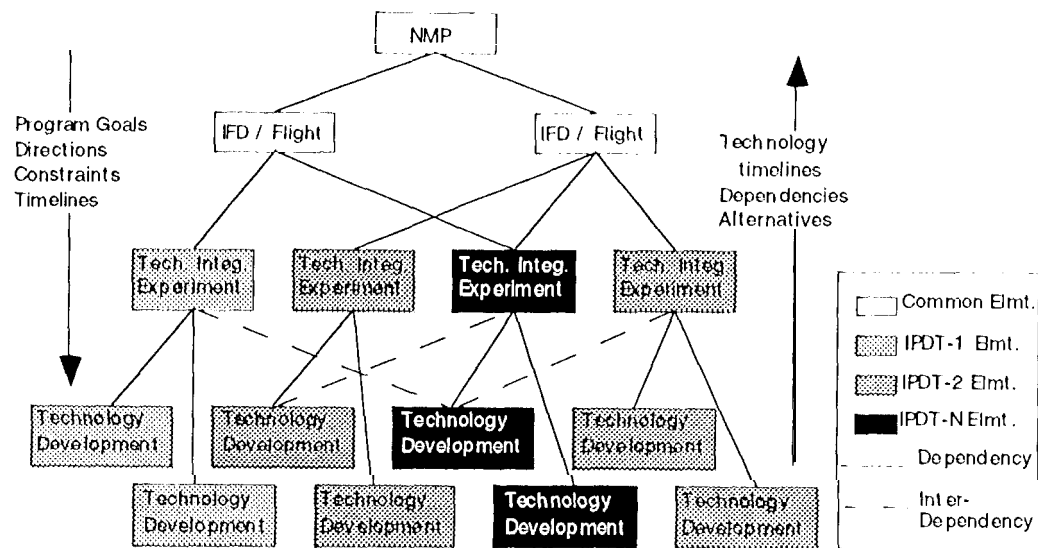
Figure 1 logical Roadmap Elements & Relationships

Further, the development of a roadmap is accomplished in a collaborative manner with overall program schedule, constraints, and goals being propagated in a top-down manner while each I PDT constructs the technology development tin-relines of the roadmap in a bottom-up manner. Completion and use of a program roadmap depends on the give and take of managing the tactical and strategic program goals within the resource budgets provided. The program roadmap tools being developed and employed allow the team to achieve this.

Roadmapping Tools

As a result of the desire to incorporate roadmapping methodology into the NMP, the Autonomy IPDT undertook prototype development of a set of World-Wide-Web tools that combine:
- database (DB) storage and organization of data with "forms-based" viewing and editing;
- dynamic generation of graphics (gifs with image maps) based on DB query results; and
- automatic generation of HTML pages.

NMP team members may select the elements of the roadmap that they are interested in viewing. An HTML query form is used for this purpose. Figure 2 illustrates a dynamically generated graphical timeline view of a segment of the Autonomy 1P] DT roadmap and some of the detailed TIE information for one of those timeline entries, accessibly directly by mousing the timeline item.
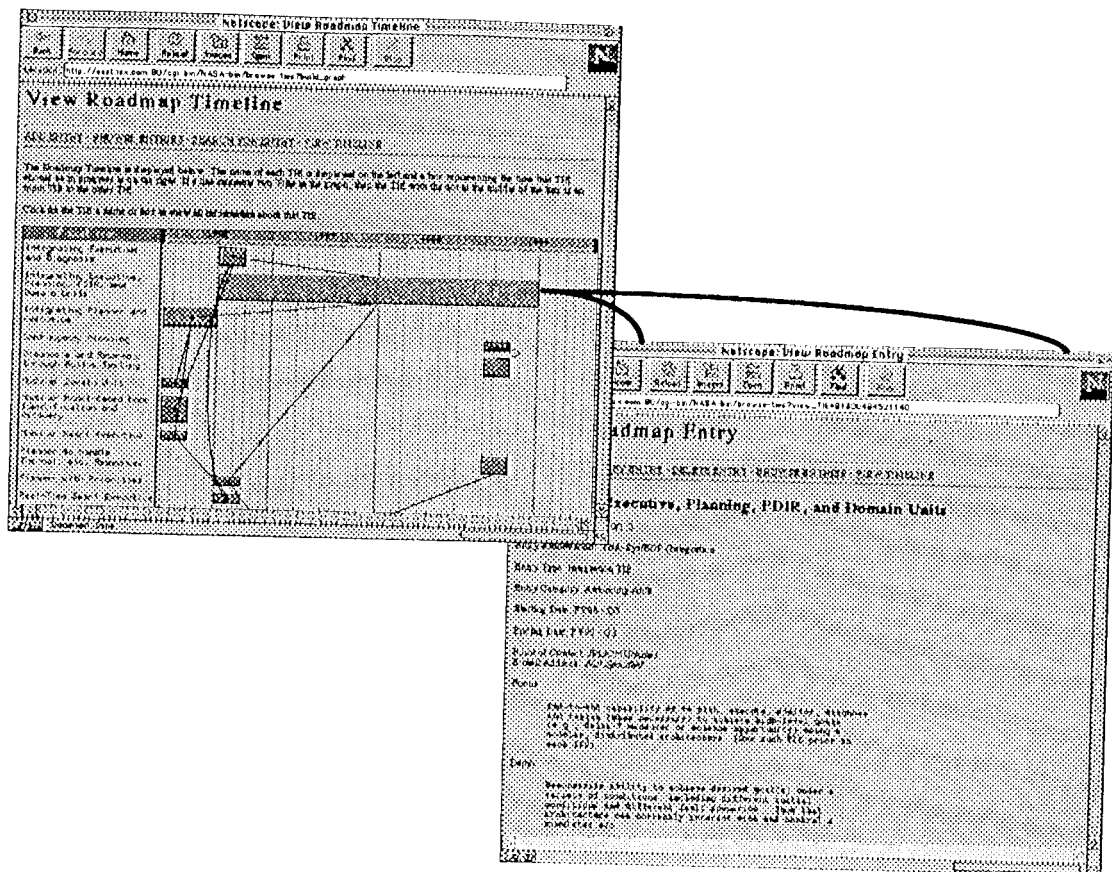
Figure 2 Graphical Timeline and Underlying Database Entry

Autonomy Roadmap

There are numerous autonomy technologies that have been identified and grouped for further maturation into integrated Feasibility Demonstrations (IFDs). The four primary autonomy 1 FDs are: Remote Agent - Autonomy Architect ure and Functional ity; Autonomous GN&C; Science & Mission Operations; and Multi-Platform Coordinated Missions. in turn, these IFDs will enable the three primary autonomy mission goals to be achieved: Self-Managing Explorer, Coordinated Platforms, and Cooperating Fleets.

Remote Agent. For the NMP, autonomy attributes are captured in a functions] mode], called the Remote Agent, as shown in Figure 3. In fact, the remote agent is the entity that carries out our desires for us remotely in space.
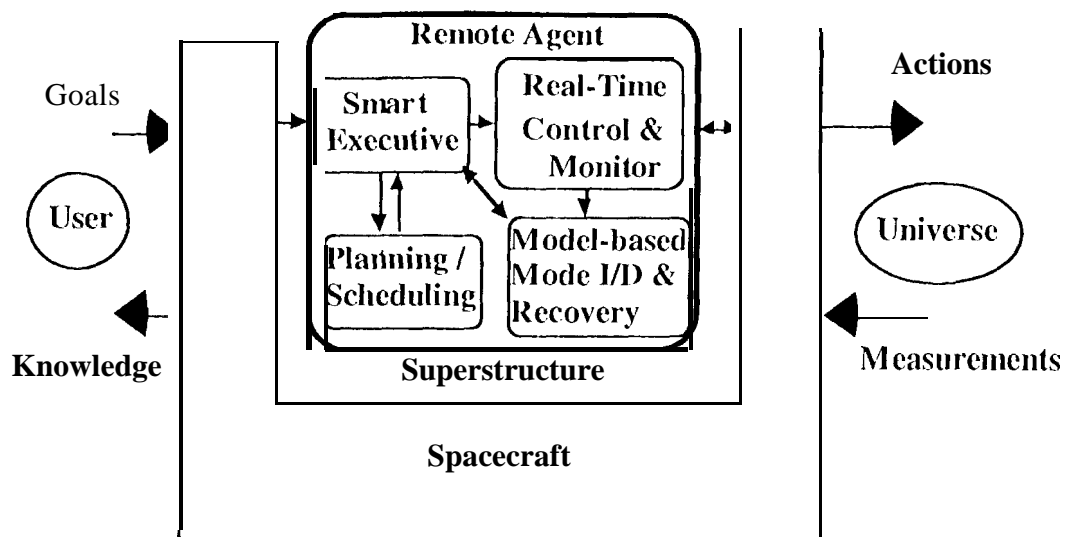
Figure 3 Remote Agent Architecture

The autonomy remote agent is the paradigm around which the New Millennium autonomous spacecraft is built. It is the core of the onboard intelligence. It has a planning and scheduling engine, a smart executive engine and a fault detection, identification and recovery engine. It also provides a scaleable plug & play architecture for domain specific autonomy functions such as autonomous navigation and control, autonomous power control and science data editing. The remote agent accepts potentially competing goals and formulates on its own a method to accomplish them in some reasonable way. The executive provides robust, event-driven plan execution and run-time decision making. The failure detection, identification and recovery engine, deduces hidden and failure states from sensors and selects recovery actions without falling into failure, states. This technology is exciting because it can reduce mission operations cost by an order of magnitude, it reduces mission specific software cost by 50% and it reduces demands on the Deep Space Network, particularly on the uplink side. Moreover, it enables opportunistic and interactive science and it enables explorations of poor] y known places.

Self-contained, autonomous capability to perform a spacecraft mission is achieved through several forms of interaction among the Remote Agent components. input of goals to the executive initiates the process. Goals may be defined *a priori* by mission designers, may be received from the ground during a mission, or may be generated by the other autonomy modules onboard the spacecraft. For example, the Mode identification and Recovery module may detect and isolate a fault which is not recoverable using one of the pre-defined recovery procedures. In this instance, the planner can be invoked to determine, a course of action to work around the fault situation, preserving the ability to perform the mission, even in unanticipated fault contexts. This *functional* redundant y is qui te disti net from the physical redundancy usually relied upon in fault protection.

A more exciting scenario is reinvocation of the planner after the capture of a science event. In this case, the planner determines activities to collect additional observations, perhaps to include altering the orbit or trajectory of the spacecraft. Autonomy for science is discussed in more detail below.

Planning and scheduling are interleaved in the Remote Agent, in additional to goals and constraints, the planner receives as input a description of the current state of the spacecraft, and a temporal horizon. The output of the planner/scheduler is a set of tokens, representing activities to be performed out to the given temporal horizon, organized in a dependency structure which reflects hard temporal constraints bet ween activities. This partiall y ordered structure, again, is quite distinct from the traditional deterministic sequence which governs spacecraft activities.

This token structure is passed to the executive for execution in the real-time context of the spacecraft. The executive expands the tokens into a sequence of low-level commands which direct] y access spacecraft subs ystems and actuators, ant] executes them, The executive also monitors the execution of these commands and when they do not succeed, has authority to retry execution of the given token expansion or to attempt execution of an alternate expansion. The executive relies on contextual information to make these decisions in the real-time situation of the spacecraft, a process termed conditional sequencing. The executive offers considerably more resilience in mission pl an execution than does traditional deterministic sequencing. If a hard command failure does occur, the executive performs actions to place the spacecraft in a safe state and reinvokes the planner to pursue an alternate approach to accomplishing mission goals.

One of the forms of contextual information drawn on by the executive is provided by the mode identification module. This module consults the latest sensor information to continuous] y determine the most likel y current mode or configurate on of each spacecraft subsystem, including failed modes. in the event that a failure is identified, predefine recovery procedures associated with the spacecraft subsystems are invoked via the executive. Should these recovery procedures fail to achieve the desired state of recovery, the p] anner can be reinvoked to pursue a work-around, updated with knowledge of the failure and its impact on spacecraft functionalist y.

Monitoring and real-time control follow fairl y traditional practice in the Remote Agent. "J'here, will likely be a need to augment onboard anomaly detecti on to address the more subtle but potentially mission-impacting anomalies currently handled by ground personnel, and not easily discernible. at the level of subsystem mode or configuration.

The planner of the Remote Agent is based on temporal database technolog y from the HSTS system [3] devel oped at NASA Ames Research Center, and on planning search engine technology from the MVP system [4] developed at the Jet Propulsion Laboratory (JPL). The executive is based on the RAPS system developed at Yale, JPL and the Univ. of Chicago [5]. Finally the mode identification and recovery module, called J ivingstone, draws on a line of model-based diagnosis research [6] origi nated at Xerox PARC and continued at NASA Ames.

Autonomous Guidance, Navigation and Control. Guidance Navigation and Control (GN&C) functions are key to delivering the spacecraft to its target and to positioning the payload to make the observations. in the past navigation was performed almost exclusively on the ground while guidance and control function consisted of low-level command sequences developed on the ground and executed on the spacecraft. The significant leap in autonomy in this key area is to develop an on board GN&C system that is based on the new spacecraft operations paradigm of "Tell the Spacecraft What to Do, NOT How and When to Do It," This paradigm, together with the philosophy of reporting to the ground only the completion of planned mission events and non-nominal engineering status data, captures our vision of a new mission operations concept with a highly autonomous spacecraft.

Figure 4 illustrated this paradigm shift for the GN&C system. Traditionally the ground mission operations team uses a two-way Doppler system to track the spacecraft for position determination and continual y monitors the spacecraft to determine its health status. Directives for target acquisition and observations require information from the spacecraft along with further planning and analysis by the ground team to generate a sequence of low level commands which is sent to the spacecraft. The sequence must be scrubbed to be free of constraint violations and errors and an elaborate procedure has been developed to accomplish this which includes an approval process down to the subsystem level. The resulting low-level time-sequenced commands are then sent to the spacecraft for execution. During execution unexpected errors trigger the fault protection system which places the spacecraft in a safe-hold mode and calls home for help.

TRADITIONAL GN&C APPROACH

AUTONOMOUS GN&C APPROACH
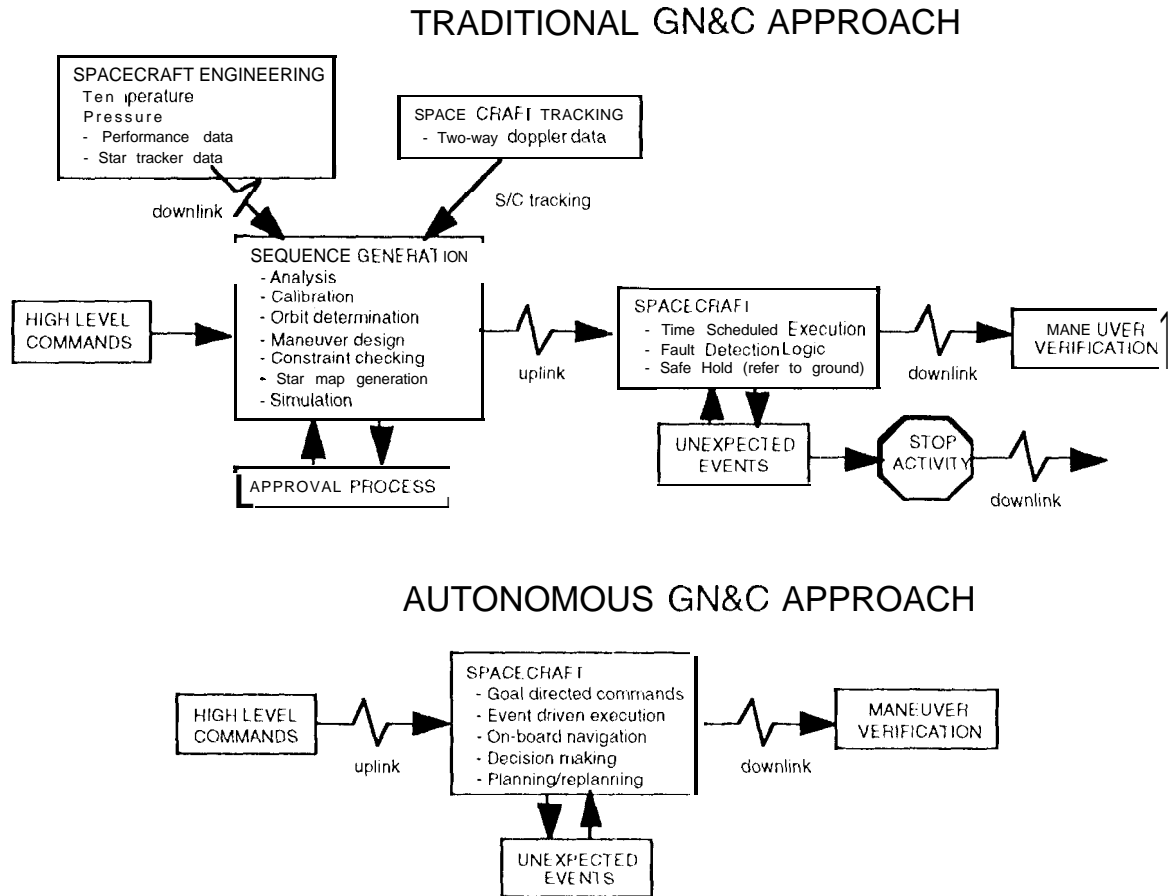
Figure 4 The new paradigm for GN&C Implementation

In the new approach shown in Figure 4 the acquisition and observation high level commands go directly to the spacecraft and the navigation and the maneuver planning and analysis is accomplished onboard. Unexpected events are largely handled by the spacecraft and alternate approaches are developed to accomplish the goals from the original request when anomalies are encountered.

'l The specialized GN&C autonomy modules that are called upon by the Remote Agent as it processes the desired high-level goals will include the following:

Onboard navigation
- optical navigation
- orbit determinate on
- trajectory correction

Maneuver execution activities
- path optimization `
- turn and burn sequence

Onboard feature recognition
- target/feature recognition
- extended body center-finding
- shape/spin determination

Target referenced Maneuvers
- Ephemeris update
- feature-based pointing
- target-relative tracking

Terminal Guidance
- onboard drag/ gravity modeling
- collision avoidance maneuvers
- terminal guidance descent and ascent

Asteroid and Comet rendezvous and sample return missions exemplify the use of the. above GN&C capabilities to reduce operation costs, reduce demands on Deep Space Network (DSN) utilization and enabling missions to bodies of unknown characteristics as summarized in Figure 5. The near-term missions will be flybys and thus the first GN&C modules to be developed will be for deep-space onboard navigation and maneuver execution.
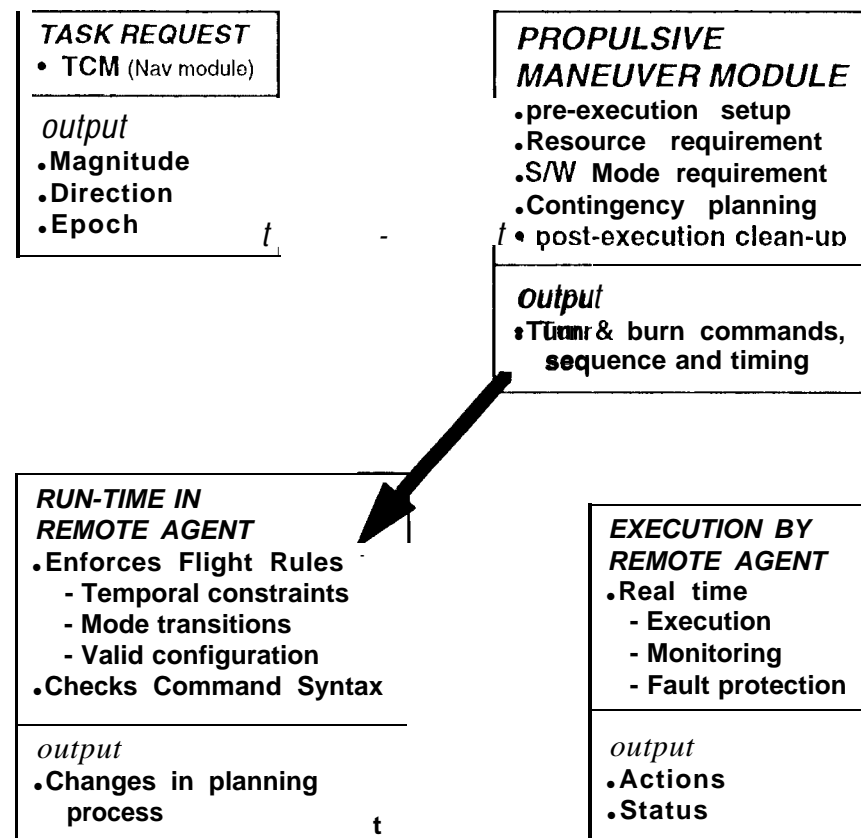
New Millennium Deep-Space Mission 1 will be the first planetary spacecraft flown with completely automated Navigation, Guidance and Control systems. The foundation of the system is an asymmetric observation process which uses deep-space images of asteroi ds and stars as the basis for orbit (position and velocity) determination. With the New Millennium DS-1 Mission being solar-electrically powered (with ion-drive engines) the principal task of the system, once the orbit is determined, is to control the engines in such a way as to deliver the spacecraft to the target body (an asteroid and 1 ater a comet) at a specified place and time. All of the necessary procedures occur on-board without ground intervention -- asteroid images are planned, taken and anal yzed; the orbit is determined; the engine throttle and direction changes are computed and implemented. Automating these processes to be handled onboard frees up these resources, thus reducing costs and enabling NASA's vision of a "virtual presence" in space -- many small spacecraft exploring the solar system -- to be realized.

Figure 5 Autonomous GN&C for Small-body Missions

Optical navigation will recognize stars, sun, earth, moon, planets and asteroids for position determination. Orbit determination computations will be performed to obtain spacecraft and target state. These will be propagated and the error to the target estimated. The required trajectory maneuvers will be determined.

Onboard navigation requires a high resolution camera (20 micro radian pixels), a 20 MIPS processing capability for short bursts <10 minutes and storage requirements are estimated to be of the order of 20 megabytes for star catalog and ephemerides. During interplanetary cruise sightings of navigation objects are required at the frequency of once a day or once every other day. Near encounter sightings requirements are more frequent and expected to be as often as several minutes.

The propulsive maneuver module develops and optimizes the path to accomplish the maneuvers computed by the navigation module. Figure 6 illustrates the implementation of this module. References 7 and 8 describe the development of this module.

TASK REQUEST
• **TCM** (Nav module)

output
.**Magnitude**
.**Direction**
.**Epoch** t

PROPULSIVE MANEUVER MODULE
.**pre-execution setup**
.**Resource requirement**
.**S/W Mode requirement**
.**Contingency planning**
t • **post-execution clean-up**

output
Turn & burn commands, sequence and timing

RUN-TIME IN REMOTE AGENT
.**Enforces Flight Rules**
  - **Temporal constraints**
  - **Mode transitions**
  - **Valid configuration**
.**Checks Command Syntax**

output
.**Changes in planning process**   t

EXECUTION BY REMOTE AGENT
.**Real time**
  - **Execution**
  - **Monitoring**
  - **Fault protection**

output
.**Actions**
.**Status**

Figure 6 Propulsive Maneuver Module implementation

Autonomous Science and Mission Operations. in order to pursue the dual goals of reducing mission costs and ultimately enabling new mission types, there is also a need for a new paradigm for performing science data evaluation and observation planning autonomous] y onboard spacecraft. The future NASA mission set will feature smaller and more numerous spacecraft in an environment of highly constrained uplink and downlink communications. The proposed paradigm for science autonomy will strike a new, more ambitious balance among: direction of mission activities by scientists without the assistance of a ground sequencing team, robust science capture and mission redirection when discoveries are made at the target body, accommodation of the realities of limited communication links, and the return of quality science products from missions.

Much of the initial focus for spacecraft autonomy has been on developing new software and systems concepts to automate engineering functions of the spacecraft: guidance, navigation and control, fault protection, resource management. However, the ultimate objectives of NASA missions are science objectives. Autonomy for science needs to be pursued as aggressive] y as autonomy for engineering, and within the same early time frame.

The specific objectives of the proposed paradigm for science autonom y are as follows: (1) To demonstrate the ability to autonomously identify features and objects of known interest in onboard acquired data and to prioritize and/or edit downlink on the basis of reliably recognizing such features and objects. (2) To provide the basis for capturing transient science events through integration of autonomous onboard science data processing with autonomous onboard capabilities for retargeting and mission planning. (3) To provide the basis for scientists to efficiently redirect mission activities following, scientific discoveries at the target body.

Telemetry limitations place extreme constraints on the scope of scientific experiments possible for deep space missions; such constraints will become even more severe in the coming era of proliferation of deep space missions. I lowever, NASA's emphasis on the development of powerful microelectronics to aggressivel y grow avail able computing resources, both in terms of CPU and memory resources, allows the scope of planned investigations to be enlarged considerably beyond those considered in the past.

We aim to demonstrate the ability of novel algorithms implemented on advanced flight computers to directly enhance the results achievable by scientific experiments onboard spacecraft. We plan to achieve this goal by implementing on board data analysis algorithms that can

1) Rapidly sift through instrument data immediately upon collection,
2) On the basis of this analysis, provide a massively condensed summary of the. important information collected by the sensor(s), either to science PI's on the ground, or to an onboard planning executive,
3) Enable adaptive control of observations based upon immediate data processing and analysis.

The objective here is to create information products that fits within telemetry limitations, but which is nevertheless sufficient for the PI or an onboard planner to adaptively direct the spacecraft so that phenomena of special interest can be focused upon by the spaceborne instruments. In general, the results of onboard analysis will be to achieve data reduction in downlink of several orders of magnitude.

I)ata reduction can take several forms. One obvious form is that of standard data compression algorithms, both lossless and lossy. The leverage available here should be pursued, but our main focus will be on more intelligent methods of data reduction. I 'or example,

1) Data editing to transmit images to ground at high resolution, but onl y of those regions from an original image that are deemed to contain significant or unexpected scientific information.
2) Retargeting of spacecraft to stud y important areas, after rapid download to earth of potentially interesting target regions and phenomena selected by onboard analysis soft ware operating in a browse mode.

We seek to enhance the scientific autonomy of spacecraft by folding scientists' knowledge and preferences into the context of spaceborne experiments during the execution of those experiments, by incorporating onboard intelligence. We aim to "close-the-loop" of tasks involving

1) data acquisition by sensors,
2) data analysis and decision-making (prioritization) by scientists, and
3) redirection of spacecraft acclivities based upon this information.

The technologies which will enable autonomy for science capabilities are data mining technologies, including pattern recognition, machine learning and knowledge discovery techniques, combined with the capabilities of the Remote Agent described above, particularly onboard planning.

There have been some notable successes in applying these technologies to large science data sets on the ground. One that is particularly relevant to the onboard science goals outlined here is the JPL Adaptive Recognition Tool (JARTool) project, which is developing trainable, adaptive object recognition technology. JARTool is a general-purpose digital image analysis tool developed to automate exploration of large image libraries.[9] It is based on the "learn by example" approach whereby a user can identify a set of objects of interest in a given image, from which a supervised learning algorithm will learn a general model to discriminate the objects of interest from the background. The first application has been to the Magellan Venus radar image set. in this application, the basic image processing itself is not straightforward. The Magellan spacecraft transmitted back to earth a data set consisting of over 30,000 high resolution radar images (SAR) of the Venusian surface. This data set is greater than that gathered by all previous planetary missions combined --- planetary scientists are literally swamped by data. The study of volcanic processes is essential to an understanding of the geologic evolution of the planet. Central to volcanic studies is the cataloging of each volcano location and its size and characteristics. There are estimated to be on the order of one million visible volcanoes scattered throughout the 30,000 images. Furthermore, it is estimated that manually locating all of these volcanoes would require on the order of 10 man-years of a planetary geologist's time. JARTool and others like it represent the starting point for developing technologies to enable onboard science analysis.

Multi-platform Coordinated Missions. NASA's vision for the 21st century of establishing a "virtual presence" in space will be supported through the use of a fleet of individual, small, inexpensive spacecraft. The use of fleets of spacecraft will allow for a dramatic reduction in any individual mission's cost, allowing scarce resources to be applied to more frequent missions and to provide a greater "virtual presence" in space. This coordinated network of spacecraft will communicate with each other in order to form a "virtual platform" in space. This "virtual platform" or fleets of multiple coordinated spacecraft will be used to enable a series of diverse, previously unimaginable applications such as the investigation of large., dynamic, complex systems or provide orders of magnitude increases in imaging capabilities.

The lifecycle cost associated with a mission can be dramatically y reduce through the use of fleets of simple, inexpensive spacecraft. By applying common manufacturing techniques, the cost of developing and testing a fleet of smaller, simpler, common spacecraft wil 1 be less expensive than the cost of developing and testing a single, large multi-instrument platform. Each individual spacecraft can be a simpler, less redundant vehicle without adverse] y affecting the overall mission capabil it ies. These fleets of spacecraft lend

themselves to being launched on smaller, less expensive launch vehicles, also adding to dramatically lower the cost associated with providing a greater "virtual presence," in space..

The investigation of large, dynamic, complex systems - such as Earth's or Mars' atmosphere will be accomplished by using closely coordinated networks of inexpensive spacecraft with each monitoring a potentially different specific spectral band. Close coordination among the net work of spacecraft will allow the spacecraft to remain synchronized thereby allowing the fusing of each individual space's data together into the desired science product. Larger areas of a planet's environment may be simultaneous] y covered, allowing for the collection of more complete data on large complex systems. New instruments can be added to a network as they are developed enabling new technology to be inserted and data set collected as required.

The detection and imaging of extremely faint objects - such as extrasolar planetary systems can be accomplished by using a tight-geometrically coupled network of spacecraft. A network of spacecraft, flying in formation as a rigid body anti combing the light received from each individual spacecraft, can function as an interferometer and dramatical 1 y increase the light gathering capability over what is currently possible.

Whether using coordinated networks of spacecraft to investigate dynamic, complex systems - such as the Earth's atmosphere - or detecting extrasolar planets, advances in new technology are required. The NMP has identified and is sponsoring advancements in the following areas:

- Inter-spacecraft communication: Networks of spacecraft will need to exchange data, share spacecraft status, and perform data fusion in order to maintain the synchronization of onboard events across platforms. NMP Communication 1 PDT is leading the inter-spacecraft communication technology development.
- Relative ranging and Absolute position knowledge: Tight-geometrically coupled network of spacecraft will need to have a highly accurate detailed knowledge of each spacecraft's relative position in order to maintain a rigid formation. A closel y coordinated networks of spacecraft needs to have accurate absolute position knowledge in order to perform scene registration and data fusion proper] y. The NMP Autonomy 11'1)'1 is working closely with academia and industry to develop a highly accurate relative ranging and absolute position capability based on existing GPS technology.
- Multi-platform sequencing: coordination of onboard events across a networks of spacecraft will require a smarter more complex onboard sequencing capability. "I'he NMP Autonomy IPDT is developing a remote agent capability to simplify the. coordination of a net work of spacecraft.
- Mission operations: Monitoring and operating a network of spacecraft will overwhelm existing capabilities, The NMP Autonomy IPDT is developing a remote agent capability to simplify the operation and maintenance of a network of spacecraft.
- Short duty cycle, long life, low impulse, thrusters: light-geometrically coupled network of spacecraft will have to maintain a highly accurate relative, position in order to maintain the required rigid formation. The Modular Architecture and Multi-functional System IPDT is working with industry to develop a solar electrical propulsion system.

DEEP SPACE 1 -- THE FIRST FLIGHT OF NEW MILLENNIUM

Each NMP flight involves selection of missions and specific technologies to be validated. The first NMP validation flight, named Deep Space 1 (1] S- 1), was selected to be a deep space asteroid and comet fl yby mission. The selection process for the mission is beyond the scope of this paper; here we will only summarize the technology selection process for DS-1. The process began with IPDT co-leaders compiling a list of candidate technologies for validation based on inputs from the IPDTs. These candidates were scored and the IPDT co-leaders provided the Readiness Probabilities to the Program office, The l'ethnology Values scores were based on three metrics and each metric was scored on a scale from zero to three in accordance with the criteria in 'liable 3,

Table 3
METRICS USED TO RANK TECHNOLOGY CANDIDATES

Metric 1: impact on 21st Century science missions	Score
•Critical for m any mission types	3
•Critical for some mission ty es and /or valuable for man	2
•Valuable for some mission types	1
•No significant impact on future missions	0
Metric 2: Revolutionary nature of breakthrough	**Score**
•A totally new approach, with an order of magnitude improvement in factors relevant to mission	3
•An improvement offering a ten-fold improvement in relevant factors	2
•An improvement offering less than a ten-fold i mprovement in relevant factors	1
•An incremental im rovement in relevant factors	0
Metric. 3: Risk reduction by flight validation	**Score**
•Flight validation is both necessary and sufficient to ensure the incorporation of this technology into future science missions	3
•Flight validation will significantly reduces the perceived risk of incorporation compared to ground 'validation al one	2
•Flight validation will reduce the perceived risk of incorporation compared to ground validation alone	1
•Flight validation offers no advantages over ground validation or ground validation alone is sufficient to ensure future incorporation	0

The Technology Value was computed as the product of the three scores. Thus the maximum technology value was 27, and the minimum was zero. The product operation was used to reflect the requirement that some of each of the metric should be present. These scores were reviewed at the Program level to ensure proper leveling across the IPDTs and to incorporate consideration of cross-cutting issues, resulting in a few modifications. After this assessment, Readiness Probability scores were similarly re.viewed by the 1> S- 1 flight leader. The Readiness Probability was then multiplied by the "l'ethnology Value to compute the Expected Technology Value score. This Expected Technology Value was the prime basis for the technologies to be flight validated on 11 S- 1. Furthermore, programmatic constraints such as funding Consideration were also factored in the final selection.

Four technology candidates were submitted by the Autonomy IPDT for 1X3-1 and they are listed in Table 4 below. The first three technologies were selected for DS-1. The last

technology was not selected due to it's low Expected Technology Value which was caused by a low score on the revolutionary nature of the technology.

Table 4
AUTONOMY TECHNOLOGY CANDIDATES AND RANKING

Technology Candidates	Expected Technology Value
• **Autonomy** remote agent	23
• Cruise o tical navigation & control	15
• Beacon mode operations	11
• Advanced celestial sensor	10

A new vision for mission operations in the 21st century will be demonstrated on 13 S- 1. The remote agent architecture will enable much more robust onboard anal ysis of spacecraft health data which can virtually eliminate the need to routinely send these data to the ground. The spacecraft will instead transmit one of four possible frequency tones that provide an assurance that the spacecraft is functioning nominally or reflect the urgency of ground intervention.   When necessary, a telemetry link will be established and the spacecraft will provide concise summaries of what has transpired since the last contact. The new technology components of beacon mode operations include: a capability for selecting and transmitting beacon tones on the spacecraft; a beacon receive station on the ground that is much simpler than what is required for full-up data capture; new techniques for adaptive onboard summarization of spacecraft data; and ground-based visualization tools for these summaries. Beacon monitor operations can reduce mission operations cost by an order of magnitude and will significantly reduce. the loading on ground station tracking resources, particularly on the downlink side.

SUMMARY

The New Millennium Program has launched an exciting new beginning in the development of tomorrow's autonomous spacecraft. The Autonomy integrated Product Development Team has created a technology roadmap spanning the next twenty years which identifies th ose technologies that are ready for insertion as well as those that are needed to accomplish both near and far term requirements. These technologies will be demonstrated through actual in-flight experience on a series of Flight Validation Missions, the first of which is planned for launch in early 1998. DS-1 will revolutionize operations of deep space and near Earth missions through the autonomy technologies described in this paper. Through these demonstrati ons and validation missions, advanced hardware and software technologies will be available for tomorrow's missions without assuming the risks inherent in their first use. This approach will accomplish NASA's vision for the 2 1st century of a "virtual presence" in space.
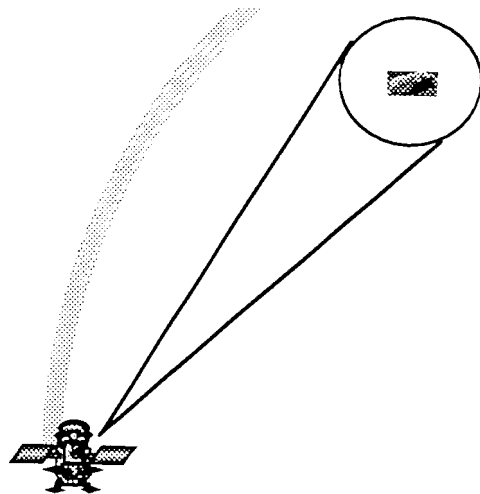
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S/C ARCHITECTURE
GOAL-DIRECTED COMMANDING
EVENT-DRIVEN SEQUENCING
RULE-BASED S/W
MANEUVER SEQUENCE GENERATION
ANOMALY RESOLUTION & ARBITRATION
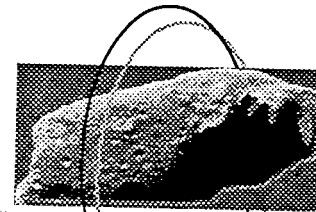S/C & ENVIRONMENT CALIBRATION
FLIGHT-RULE COMPLIANCE

RENDEZVOUS
CORRECTIONS TO S/B EPHEMERIDES
S/B CHARACTERIZATION
        shape, size and dynamics
MANEUVER
        planning, execution & monitoring

ORBITAL OPERATIONS
S/B CHARACTERIZATION
ORBIT DETERMINATION &
CONTROL
SITE SELECTION

CRUISE
SMALL-BODY (S/B) SEARCH & ACQUISITION
ON-BOARD OPTICAL NAVIGATION
EPHEMERIDES UPDATE
ON-BOARD TRAJECTORY RE-PLANNING
MANEUVER SEQUENCE -development,
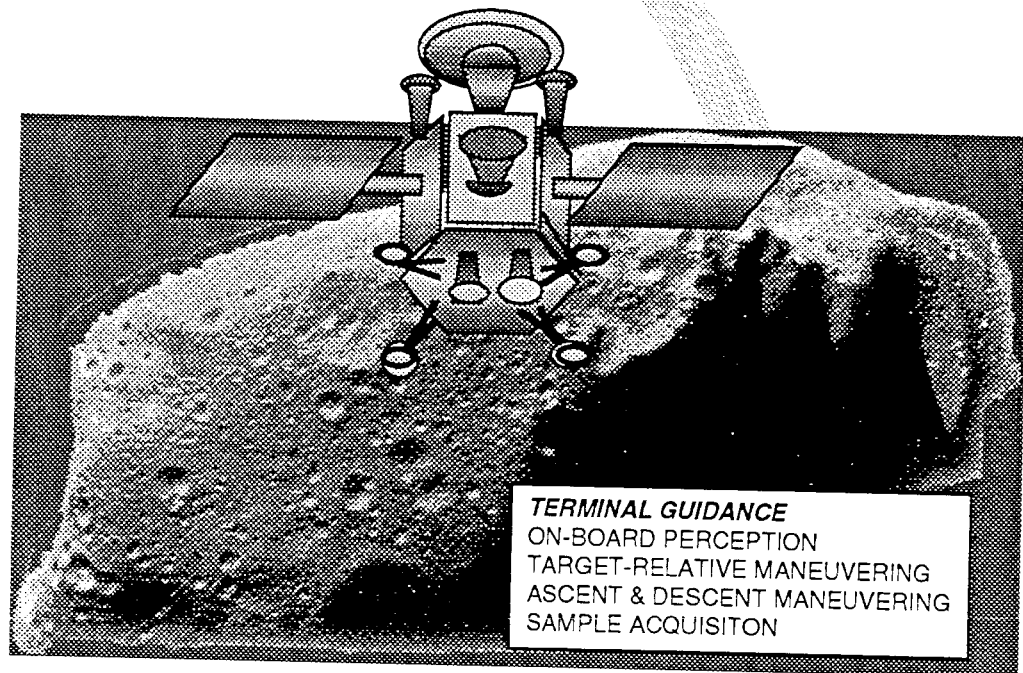   execution & monitoring

TERMINAL GUIDANCE
ON-BOARD PERCEPTION
TARGET-RELATIVE MANEUVERING
ASCENT & DESCENT MANEUVERING
SAMPLE ACQUISITON